OPTIMAL DESIGN OF COUNTER AND CROSS FLOW PACKED BED TOWERS FOR AMMONIA REMOVAL

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

by

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to the

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

MAY, 1938

CERTIFICATE

Certified that the work presented in this thesis entitled **Optimal Design of Counter and Cross Flow Packed Bed Towers for Ammonia Removal** by Mr Purnendu Bose has been carried out under my supervision and has not been submitted else where for a degree.

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ACKNOWLEDGEMENT

I wish to take this opportunity to express my deep sense of respect and gratitude to Dr. Vinod Tare for his guidance throughout this work.

I also acknowledge the help provided to me by the members of the faculty of my department during my stay at IIT Kanpur.

I am grateful to my friends at IIT Kanpur for making my stay here memorable. Also I thank all persons connected with processing of text and figures of this thesis.

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NOMENCLATURE

A : L/G . $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.

A_c : Area of the tower in the direction perpendicular to the air flow. $M^{\emptyset}L^{2}T^{\emptyset}$, m^2.

A_p : Specific surface area of packing. $M^{\emptyset}L^{-1}T^{\emptyset}$, cm^{-1}.

A^c : Area of cross section of the tower. $M^{\emptyset}L^{2}T^{\emptyset}$,m^2.

B : Width of the tower in the direction perpendicular to that of air flow. $M^{\emptyset}LT^{\emptyset}$, m.

BB : $\Delta w/H_{tG}$. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.

C_1 : Cost of fans. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_2 : Cost of pumps. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_3 : Cost of tower structure. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_4 : Exterior and electrical cost. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_5 : Cost of distribution system. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_6 : Cost of packing. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_7 : Fan power cost. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_8 : Pump power cost. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_9 : Cost of chemicals, labour and supplies. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year

$C_{1\emptyset}$: Cost of heating water. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

C_{11} : Cost of heating air .$M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

CCI : Engineering news record construction cost index. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.

CRF : Capital recovery factor. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.

C_k : Power cost. $M^{-1}L^{-2}T^{2}$, cents/kw-hr.

C_p : Specific heat of water. $M^{\emptyset}L^{2}T^{-2}$, k cal/kg/ C.

C_w : Cost of packing. $M^{\emptyset}L^{-3}T^{\emptyset}$, \$/m^3.

c : The factor by which penalty parameter is reduced after each SUMT cycle. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.

E_f : Efficiency of fan. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.

E_p	: Efficiency of pumps. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
f	: Fanning friction factor. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
F	: Objective function. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.
F_G	: Gas transfer coefficient. $ML^{-2}T^{-1}$, moles/hr/m^2.
G	: Gas flow rate at any level in the tower. $ML^{-2}T^{-1}$, moles/hr/m^2.
G_1	: Total gas flow rate at the entrance to the tower. $ML^{-2}T^{-1}$, moles/hr/m^2.
G_2	: Total gas flow at the exit from the tower. $ML^{-2}T^{-1}$, moles/hr/m^2.
G_E	: Equivalent air mass velocity for pressure drop relations. $ML^{-2}T^{-1}$, moles/hr/m^2.
G_S	: Flow rate of the solvent gas. $ML^{-2}T^{-1}$, moles/hr/m^2.
G'	: Air mass flow rate. $ML^{-2}T^{-1}$, kg/hr/m^2.
H_S	: Horizontal spacing between wood slats used as packing. $M^{\emptyset}LT^{\emptyset}$, cm.
H_T	: Horizontal thickness of wood slats used as packing. $M^{\emptyset}LT^{\emptyset}$, cm.
H_{tG}	: Height of transfer unit for ammonia transfer. $M^{\emptyset}LT^{\emptyset}$, m.
HT	: Height of transfer unit for cooling. $M^{\emptyset}LT^{\emptyset}$, m.
h	: Enthalpy of air. $M^{\emptyset}L^2T^{-2}$, kcal/kg.
h_j	: Enthalpy of gas at the entrance to the j th element. $M^{\emptyset}L^2T^{-2}$, kcal/kg.
h_{cj}	: Enthalpy of air at the center of j th element. $M^{\emptyset}L^2T^{-2}$, kcal/kg .
h^*_{cj}	: Enthalpy of air at the center of the j th element corresponding to the water temperature. $M^{\emptyset}L^2T^{-2}$, kcal/kg.
h_{ij}	: Enthalpy of air at the entrance of element (i j). $M^{\emptyset}L^2T^{-2}$, kacl/kg.
h_{cij}	: Enthalpy of air at the center of element (i j). $M^{\emptyset}L^2T^{-2}$, kcal/kg.
h^*_{cij}	: Enthalpy of air at the center of element (i j) corresponding to the water temperature. $M^{\emptyset}L^2T^{-2}$,

I	:	Rate of intrest. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
L	:	Total liquid flow rate at any level in the tower. $ML^{-2}T^{-1}$, moles/hr/m^2
L_1	:	Total liquid flow rate at the exit from the tower. $ML^{-2}T^{-1}$, moles/hr/m^2.
L_2	:	Total liquid flow rate at the entrance of the tower. $ML^{-2}T^{-1}$, moles/hr/m^2.
L_S	:	Flow rate of solvent liquid. $ML^{-2}T^{-1}$, moles/hr/m^2.
L'	:	Mass flow rate of liquid. $ML^{-2}T^{-1}$, moles/hr/m^2.
M_A	:	Average molecular weight of air .$M^{\emptyset}L^{\emptyset}T^{\emptyset}$
M_W	:	Molecular weight of water. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
m	:	Henry's law constant. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
N_A	:	Rate of gas transfer. $ML^{-2}T^{-1}$, moles/hr/m^2.
N_{tG}	:	Number of transfer units . $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
n	:	Design period. $M^{\emptyset}L^{\emptyset}T$, years.
P_c	:	Fraction of time the tower is in operation. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
Q	:	Flow rate of water into the tower. $M^{\emptyset}L^{3}T^{-1}$, million litres/day.
r	:	Penalty parameter. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
S_F	:	The vertical fall of a water drop, used in pressure drop calculations. $M^{\emptyset}LT^{\emptyset}$, cm.
Ta	:	Initial temperature of air before heating. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$ degree C.
Ta_1	:	Temperature of air entering the tower . $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C.
Ta_j	:	Temperature of air at the exit from j th element. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C.
Ta_{ij}	:	Temperature of air at the entrance to element (i j) $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C.
Tw	:	Temperature of water before heating. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C.
Tw_1	:	Temperature of water entering the tower. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C.

Tw_j : Temperature of water at the entrance of the j th element. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C.

Tw_{ij} : Temperature of water at the entrance of element (i j). $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C

$Tw^c{}_j$: Temperature of water at the center of the j th element. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C.

$Tw^c{}_{ij}$: Temperature of water at the center of element (i j). $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, degree C

TC : Total cost of the system. $M^{\emptyset}L^{\emptyset}T^{-1}$, \$/year.

V_S : Vertical spacing between wood grids used as packing. $M^{\emptyset}LT^{\emptyset}$, cm.

V_T : Vertical thickness of wood grids used as packing. $M^{\emptyset}LT^{\emptyset}$, cm.

W : Width of crossflow ammonia stripping tower parallel to the direction of air flow. $M^{\emptyset}LT^{\emptyset}$, m.

X : Design vector. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.

XAV : Average ammonia concentration in water at certain level in a crossflow tower. $ML^{-3}T^{\emptyset}$, mg/l.

x : Concentration of ammonia in water at any level in the tower. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.

x_{AL} : Concentration of ammonia in liquid phase. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.

x_{all} : Maximum ammonia concentration in effluent water. $ML^{-3}T^{\emptyset}$, mg/l.

x_{Ai} : Saturation concentration of ammonia in liquid phase $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.

x_{cj} : Ammonia concentration at the center of j th element. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.

x_{cij} : Ammonia concentration at the center of element (i j) $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.

x_{final} : Ammonia concentration in effluent water. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mg/l.

$x_{initial}$: Ammonia concentration in influent water. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mg/l.

x_{ij} : Ammonia concentration in water entering element (i j). $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fraction.

x_j : Ammonia concentration in water entering j th element. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fraction.

y	:	Ammonia concentration in gaseous phase at any level in the tower. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fraction.
y_{AG}	:	Ammonia concentration in gaseous phase. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fraction.
y_{Ai}	:	Saturation ammonia concentration in gaseous phase. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fraction.
y^{*}_{cj}	:	Ammonia concentration in air at the center of the j th element in equilibrium with ammonia in liquid phase. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fraction.
y^{*}_{cij}	:	Ammonia concentration in air at the center of element (i j) in equilibrium with ammonia in liquid phase. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fraction.
y_{cj}	:	Ammonia concentration in air at the center of j th element. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.
y_{final}	:	Ammonia concentration in effluent gas. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.
$y_{initial}$	:	Ammonia concentration in influent gas. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$,mole fractions.
y_{ij}	:	Ammonia concentration in air entering element (i j) of the tower. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.
y_{j}	:	Ammonia concentration in air at the entrance to the j th element of a tower. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$, mole fractions.
Z	:	Height of the tower. $M^{\emptyset}LT^{\emptyset}$, m.
ρ	:	Density of air. $ML^{-3}T^{\emptyset}$, kg/m^3.
φ	:	Penalty function. $M^{\emptyset}L^{\emptyset}T^{\emptyset}$.
ΔP	:	Pressure drop in cm of water. $M^{\emptyset}LT^{\emptyset}$,cm.
ΔP_1	:	Pressure drop caused by filling and support members in crossflow towers in cm of water. $M^{\emptyset}LT^{\emptyset}$, cm.
ΔP_2	:	Pressure drop due to obstruction by water drops in cm of water in a crossflow tower. $M^{\emptyset}LT^{\emptyset}$, cm.
Δw	:	Incremental width. $M^{\emptyset}LT^{\emptyset}$, m.
Δz	:	Incremental height. $M^{\emptyset}LT^{\emptyset}$, m.

ABSTRACT

Ammonia stripping is a widely used process for removal of ammonical nitrogen from water. However, the expenditures involved, both in terms of capital, and operation and maintenance costs, are quite considerable. Thus even a few percent saving at the design stage would be of significant value. In the present study an attempt is made to develop a rational approach to minimum cost design of ammonia stripping towers. Procedures for optimal design of both counterflow and crossflow ammonia stripping towers are developed. The feasibility of preheating water and/or air for improving the efficiency of ammonia removal has also been investigated. Optimization problem is framed as minimisation of capital and operational cost subject to the constraints determined by process requirements. Interior penalty function method has been used as an optimization technique. Results show that in most of the cases crossflow towers are efficient than counterflow towers. The results also indicate that the option of preheating water and/or air to improve ammonia removal efficiency may be worth considering in some situations.

KEYWORDS

Gas transfer, Ammonia stripping, Packed bed towers, Counterflow towers, crossflow towers, Non - linear programming, optimization, Least cost design.

INTRODUCTION

Various compounds containing nitrogen are becoming increasingly important in wastewater management programs because of the many effects that nitrogenous materials can have on the environment. Nitrogen in its various forms, can deplete dissolved oxygen levels in receiving waters, stimulate aquatic growth, exhibit toxicity towards aquatic life, affect chlorine disinfection efficiency, present public health hazard, and affect suitability of water for reuse. Major processes for removing nitrogen from wastewater are biological nitrification-denitrification, break point chlorination, selective ion exchange for ammonia removal, and air stripping for ammonia removal (ammonia stripping). These are the processes which are technically and economically most viable at the present time. Out of these methods, ammonia stripping is one of the most economical means of nitrogen removal. The ammonia stripping concept is based on very simple principles. Due to its simplicity, it offers a reliable means of ammonia removal when applied under appropriate conditions. Ammonia stripping is carried out in stripping towers. There are two basic types of towers now being used in full scale operation: counter current and cross current towers.

Design parameters for ammonia stripping towers include air to liquid ratio, tower depth and loading rates. Proper choice of these variables is required for efficient and economical nitrogen removal. Also the efficiency of ammonia stripping towers depend on the influent water and air temperature, with efficiency of ammonia removal reducing drastically at low temperatures. So an attempt should be made to study

the feasibility of preheating air and/or water for improved ammonia removal efficiency.

Ammonia stripping towers are mostly designed using empirical design procedures. Performances of stripping towers have been documented from pilot plant studies. Pilot plant studies of ammonia stripping were conducted (Slechta and Culp, 1967; EPA, 1971) at South Tahoe public utility district. Based on these studies it was suggested that a liquid loading rate of 5000 $kg/hr/m^2$ is compatible with efficient tower operation at 6 to 7 m packing depth. Pilot studies were also conducted in Orange County water district (Wesner and Argo, 1973) and they proposed an air to liquid ratio of 3000 m^3/m^3. Effect of temperature on ammonia removal was studied at the Blue Plains plant in Washington D.C. (O'Farrel et al., 1973). It was reported that at 10^oC the maximum practical removal efficiency drops to about 75 percent. Voluminous literature is also available on the practical aspects of the operation of the ammonia stripping towers (Culp and Culp, 1971; Gonzales and Culp, 1973; Kepple, 1973 and Culp, 1974). Based on various pilot plant studies Environmental Protection Agency, USA published a manual on nitrogen removal (EPA, 1975) which covers many aspects of the design of ammonia stripping towers.

A review of the literature related to ammonia removal using packed bed towers reveals that many investigations have been carried out in the last two decades to improve upon the design procedures, practical aspects, and hence performance of packed bed towers. These investigations deal with mathematical modelling (Snow and Wnek, 1969; Roesler et al., 1970, 1971), development of computer programs for analysis of temperature profiles in the tower (Chiem et al., 1981), improved mass transfer models (Rolf et al., 1982), hydraulics of

packed bed towers (Billet, 1983), application of absorption data for design and scale up of packed bed towers (Billet and Mackowick, 1984), etc. An attempt on optimization of ammonia removal from wastewater was made by Rozhdov and Skidan (1980). A simulation model was described for optimization of removal of ammonia from wastewater by desorption of ammonia after alkali pretreatment, followed by oxidation of residual ammonia with active chlorine. This model makes it possible to determine the optimal values of such parameters as aqueous phase pH, air consumption, tower cross section, packed height of raschig ring and chlorine and lime dose. A model for optimization of packed tower based on optimal calculation of the gas flow pressure drop relative to a group of system variables was proposed by Rodriguez et al (1986). However, these investigations emphasised on maximizing ammonia removal efficiency instead of minimum cost design. The present study specifically focuses on this aspect of the ammonia striping towers.

SCOPE

The major objective of the present study is to evolve a procedure for minimum cost (optimal) design of ammonia stripping towers. An analysis of the design procedure (Roesler et al., 1971) indicate that the equations involved are nonlinear in nature which necessitate application of nonlinear optimization techniques. Interior Penalty function method (Rao, 1978) which is a popular and versatile technique for nonlinear optimization is used. Specifically, the entire work was directed on the following lines:

1. Development of analysis and design procedure for counterflow ammonia stripping towers.

2. Development of analysis and design procedure for crossflow ammonia stripping towers.

3. Formulation of procedure for optimal design of counter and cross flow ammonia stripping towers with and without the option of preheating influent air and/or water.

4. Evaluation of cost functions for various components influencing the process, including the cost of preheating water and/or air.

5. Analysis of the optimization results.

THEORETICAL BACKGROUND

The process of ammonia stripping consists of transfering ammonia gas dissolved in water to air which is in contact with water. The usefulness of ammonia stripping tower lies in the fact that it helps this transfer to occur in an efficient way.

Equilibrium Relationship

To study the process of ammonia stripping, it is convenient to first consider the equilibrium relationships. The relationship between concentration of ammonia in water and air can be depicted as shown in Fig. 1. The initial portion of this curve may be approximated by a

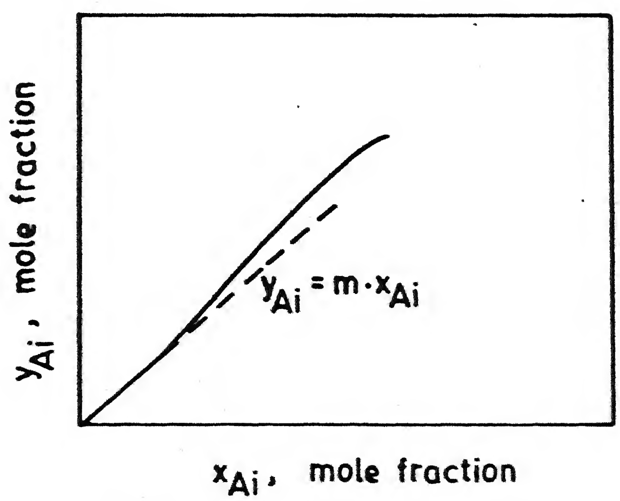

Fig. 1. Equilibrium distribution of ammonia between a gas and a liquid phase at constant temperature.

straight line. If the slope of this line is m, then the concentration of ammonia in water and air can be related by the expression

$$y_{Ai} = m \cdot x_{Ai} \qquad \text{................(01)}$$

where, y_{Ai} is the equilibrium concentration of ammonia in air, x_{Ai} is the equilibrium concentration of ammonia in water, and m is a constant. This relationship is also known as Henry's law of diffusion. For dilute solutions (ammonia concentration < 5000 mg/l, Treybal, 1980) this law gives good approximation of the actual situation. Thus, in general, whenever a substance is dissolved between two insoluble phases, a dynamic equilibrium is established with equilibrium concentrations governed by Henry's law.

The curve shown in Fig. 1 is unique for a particular liquid-gas system and the substance to be transferd. Nevertheless the following principles are common to all systems involving distribution of a substance between two insoluble phases.

1. For a fixed set of conditions, i.e. temperature and pressure, there exists an equilibrium relationship which may be shown graphically in the form of an equilibrium distribution curve by plotting the equilibrium concentrations in the two phases one against the other.

2. For a system in equilibrium, there is no net diffusion of components between the two phases.

3. For a system not in equilibrium, diffusion of components between the phases will occur in such a manner as to bring the system to a condition of equilibrium. If sufficient time is available, equilibrium concentrations will eventually prevail.

Rate of Mass Transfer

The mass transfer takes place according to the two film theory (Fig. 2). According to this theory there is no resistance to solute transfer across the interface separating the phases, and as a result the concentrations at the interface of the two phases are equilibrium concentrations. Mathematicaly,

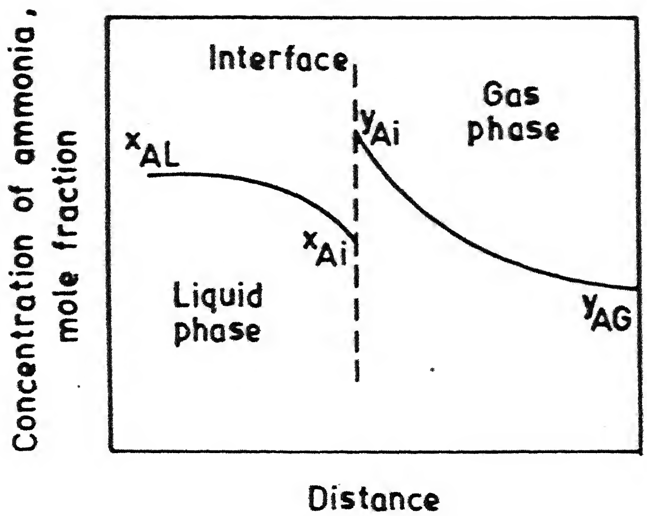

Fig. 2. The two film theory concept.

$$N_A = F_G \ln\left[\frac{1 - y_{Ai}}{1 - y_{AG}}\right] \qquad \text{..................(02)}$$

where, N_A is the rate of gas transfer/unit area, F_G is the gas transfer coefficient, and y_{AG} is the ammonia concentration in gaseous phase. Thus it is evident that for efficient mass transfer:

1. The driving force i.e. the departure of the system from equilibrium should be more.
2. The area provided for mass transfer should be more.

The first condition is achieved by letting water and air mix in a certain way i.e. in counter or cross current mode. The second condition is achieved by packing the tower. Packing is usually provided to minimize the film resistance to gas transfer by continuous forming, splashing and reforming of drops.

ANALYSIS OF COUNTERFLOW TOWERS

The detailed analysis of counterflow ammonia stripping tower has been presented by Treybal (1980). According to this analysis, the height of the packed bed tower (Z) can be expressed as

$$Z = H_{tG} \cdot N_{tG} = H_{tG} \int_{y_{final}}^{y_{initial}} \frac{dy}{y - y_{Ai}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(03)$$

where, H_{tG} is the height of transfer unit for ammonia transfer, N_{tG} is the number of transfer units, and $y_{initial}$, y_{final} and y are the ammonia concentrations in gas phase at the inlet, exit and at any level respectively in the tower.

Solution Procedure

The design of packed bed tower for ammonia removal requires evaluation of both temperature and ammonia concentration profiles in the tower. Distribution and rate of ammonia transfer between liquid and gaseous phase are dependent upon temperature and hence temperature profile in the tower has to be evaluated first.

Computation of Temperature Profile

The schematic diagram of the counter flow ammonia stripping tower is given in Fig. 3. The tower is divided into elements and each element is solved separately starting from bottom of the tower. Since the concentration of ammonia in both water and air is very less, it can be safely assumed that

$G_1 = G_2 = G$, and

$L_1 = L_2 = L$

where, G_1, G_2 and G are the total gas flow rates at the entrance, exit and at any level respectively in the tower, and L_1, L_2 and L are the corresponding total liquid flow rates. The equations used for the computation of temperature profile are developed based on heat balance and heat transfer for an isolated element (Fig. 4), and can be written as follows (Mc A dams, 1954).

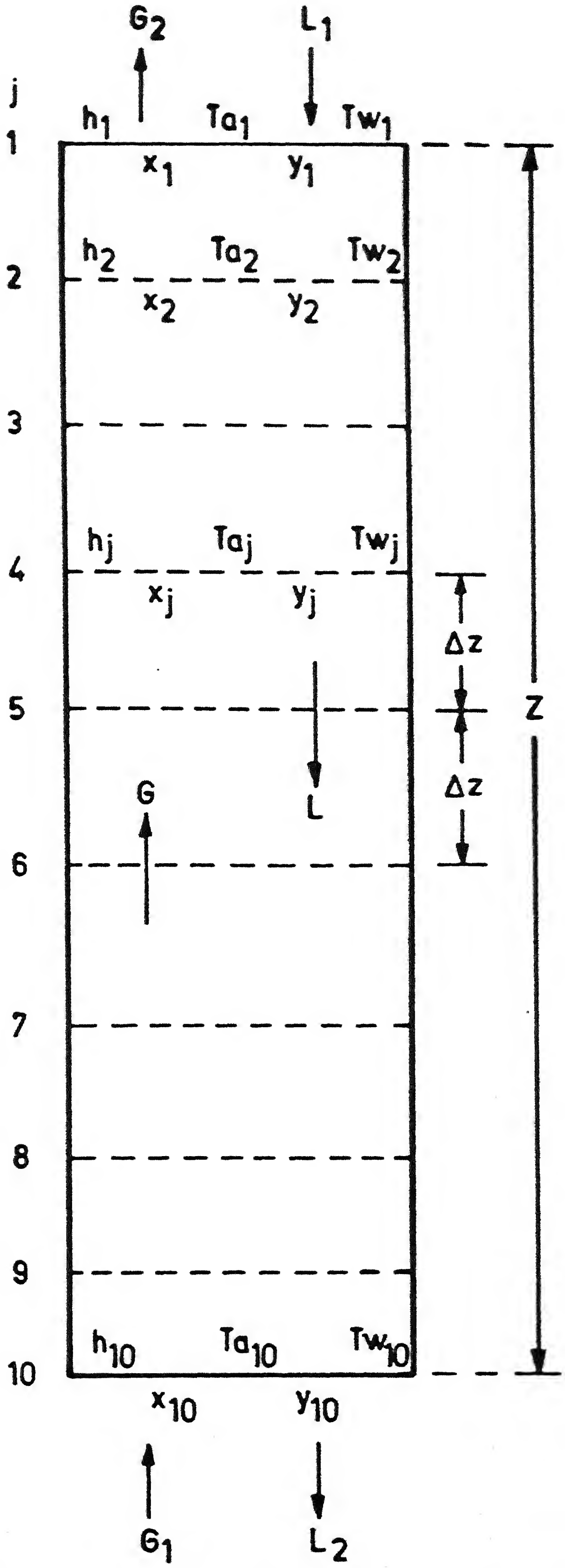

Fig. 3. Schematic representation of counterflow ammonia stripping tower

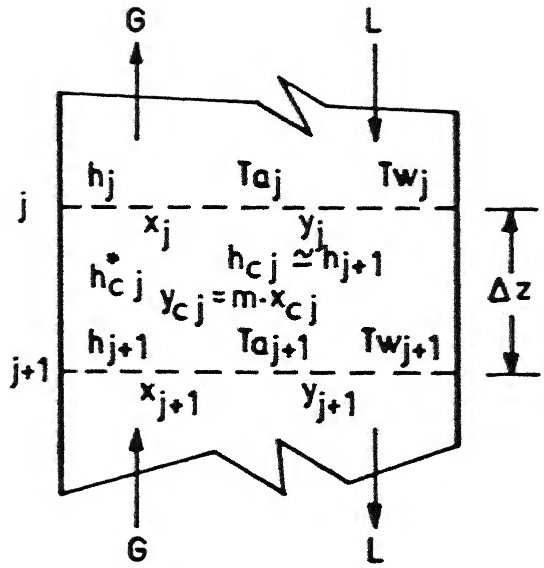

Fig. 4. Details of an element of counter flow ammonia stripping tower.

$$G' (h_j - h_{j+1}) = L' C_p (Tw_j - Tw_{j+1}) \qquad \text{.................(04)}$$

$$(h_j - h_{j+1}) = (1/HT) (h^*_{cj} - h_{cj}) \Delta z \qquad \text{.................(05)}$$

where, G' and L' are air and liquid mass flow rates respectively, HT is the height of transfer unit for cooling, h_j and h_{cj} are the enthalpies of air at the entrance and at the centre of the j th element respectively, h^*_{cj} is the enthalpy of air at the centre of the j th element corresponding to the temperature of water, C_p is the specific heat of water, Tw_j is the temperature of water at the entrance of the j th element, and Δz is the incremental height. The value of HT can be determined empirically as mentioned by Roesler et al (1971).

$$HT = (407.03/A_p) (L'/G')^{0.3} \qquad \text{.................(06)}$$

Here, A_p, the specific surface area of packing is given by

$$A_p = 60.96 (H_T + V_T)/(H_S \cdot V_S) \qquad \text{.................(07)}$$

where, H_T, V_T, H_S and V_S are horizontal thickness of wood slats, vertical thickness of wood slats, horizontal spacing between wood slats and vertical spacing between wood slats used as packing respectively. Empirical regression relationships (Perry, 1963) are used to correlate wet-bulb temperature and enthalpy of air as

$$h = 0.5542 [0.00008 (1.8 Ta + 32)^3 - 0.0064 (1.8 Ta +32)^2$$
$$+ 0.54789 (1.8 Ta + 32) - 1.62754] \qquad \text{.................(08)}$$

$$Ta = 0.555([0.00016632 (h/0.5542)^3 - 0.036058 (h/0.5542)^2$$
$$+ 3.1195 (h/0.5542) - 0.39736] - 32.0) \qquad \text{.................(09)}$$

where, h is the enthalpy of air, and Ta is the temperature of air. The flow chart for computation of temperature profile is presented in Fig. 5.

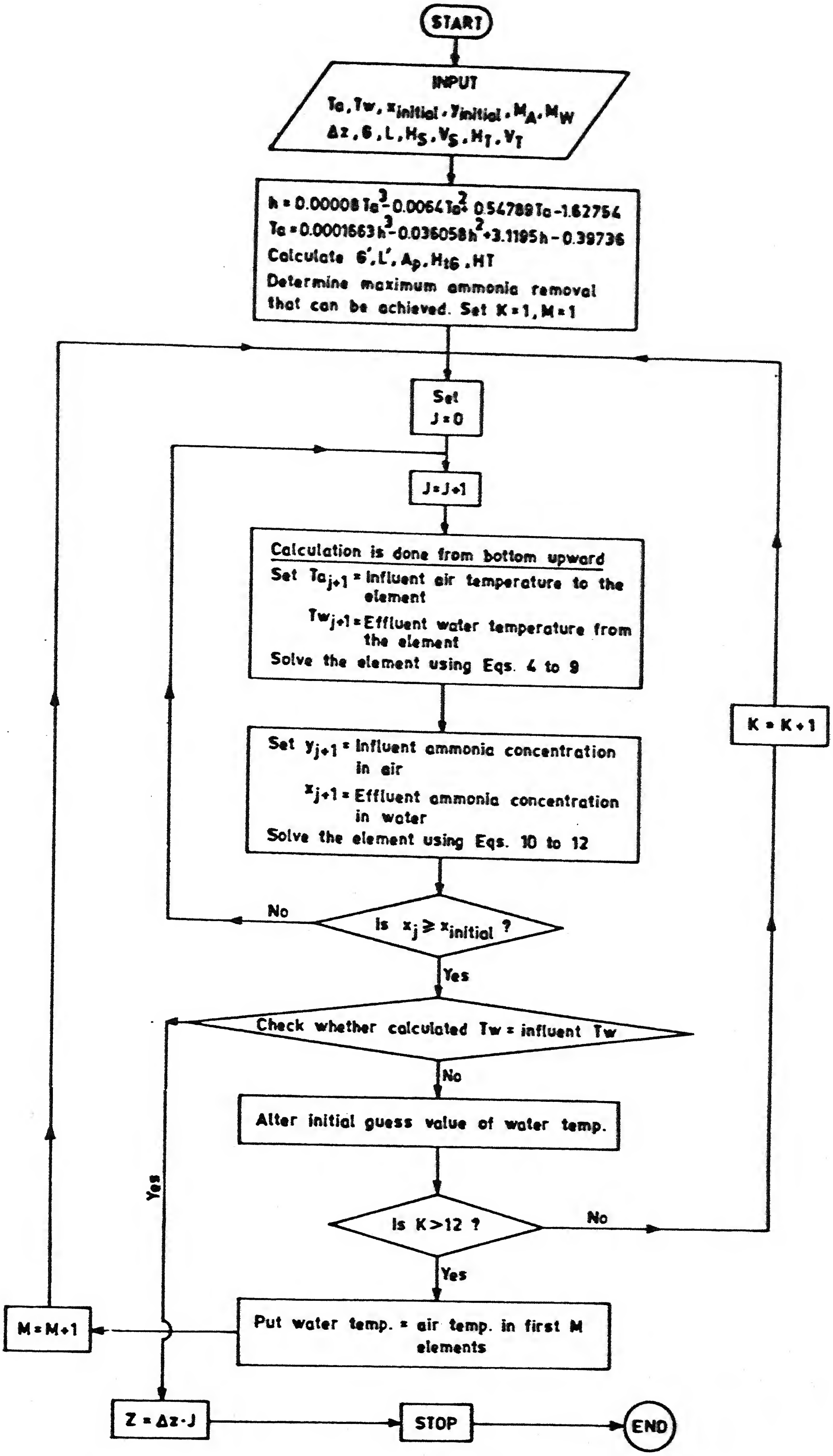

Fig. 5. Flow chart for computing temperature and ammonia concentration profiles in counterflow ammonia stripping tower.

Computation of Ammonia Concentration Profile

The equations used for the computation of ammonia concentration profile are developed based on mass balance and mass transfer relations with reference to Figs. 3 and 4.

$$G\,(y_j - y_{j+1}) = L\,(x_j - x_{j+1}) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(10)$$

$$y_j - y_{j+1} = (1/H_{tG})\,(y^*_{cj} - y_{cj})\,\triangle z \qquad \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

Eq. 11 is the difference form of Eq. 3. Here, y_j and y_{cj} are ammonia concentration in gaseous phase at the entrance and at the centre of the j th element respectively, y^*_{cj} is the ammonia concentration in gaseous phase at the centre of j th element in equilibrium with ammonia concentration in water, and x_j is the ammonia concentration in liquid phase at the entrance of the j th element. The value of H_{tG} is given as follows (Roesler et al., 1971).

$$H_{tG} = 2.929\,(G/L)^{1.322} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(12)$$

The computational procedure for ammonia concentration profile is presented in Fig. 5.

Computation of Air Pressure Drop

The air pressure drop in a counterflow packed bed ammonia stripping tower is a function of tower height, air flow rate and the nature of packing. Generally an empirical correlation (Johnstone and Singh, 1937) is employed for the computation of pressre drop.

$$\triangle P = 0.482 \,.\, f \,.\, z \,.\, (G')^{1.8} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(13)$$

where, $\triangle P$ is the air pressure drop in cm of water, and f is the fanning fraction factor (Table 1).

ANALYSIS OF CROSSFLOW TOWERS

The detailed analysis of crossflow ammonia stripping tower has been presented by Thibodeaux (1969). According to this analysis, the

Table 1. Friction factors corresponding to various wood grid sizes. (H_T = 0.0635 cms)

$V_T = V_S$	H_S	$f \times 10^8$
2.54	1.5875	18.90
5.08	1.5875	13.70
10.16	1.5875	8.30
20.32	1.5875	5.70
10.16	3.1750	2.43
20.32	3.1750	1.79
30.48	3.1750	1.20
10.16	4.4450	1.73
20.32	4.4450	1.16
30.48	4.4450	0.95
10.16	5.7150	0.87
20.32	5.7150	0.68
30.48	5.7150	0.63

incremental width $\angle w$ of a crossflow tower can be expressed as

$$\angle w = \int_{y_{i+1\ j}}^{y_{ij}} \frac{dy}{y - y_{Ai}} \cdot H_{tG} \qquad \text{................(14)}$$

where, y_{ij} is the ammonia concentration in gaseous phase at the entrance to the element (i j).

Solution Procedure

The schematic diagram of the crossflow tower is shown in Fig. 6. Similar to the analysis of counterflow tower, analysis of crossflow tower involve two steps, viz., calculation of temperature and ammonia concentration profiles.

Computation of Temperature Profile

The schematic diagram of the crossflow ammonia stripping tower is given in Fig. 7. The tower is divided into elements and each element is solved separately. The details of a typical element are shown in Fig. 8. The following two equations (McAdams, 1954) are used for the computation of the temperature profile.

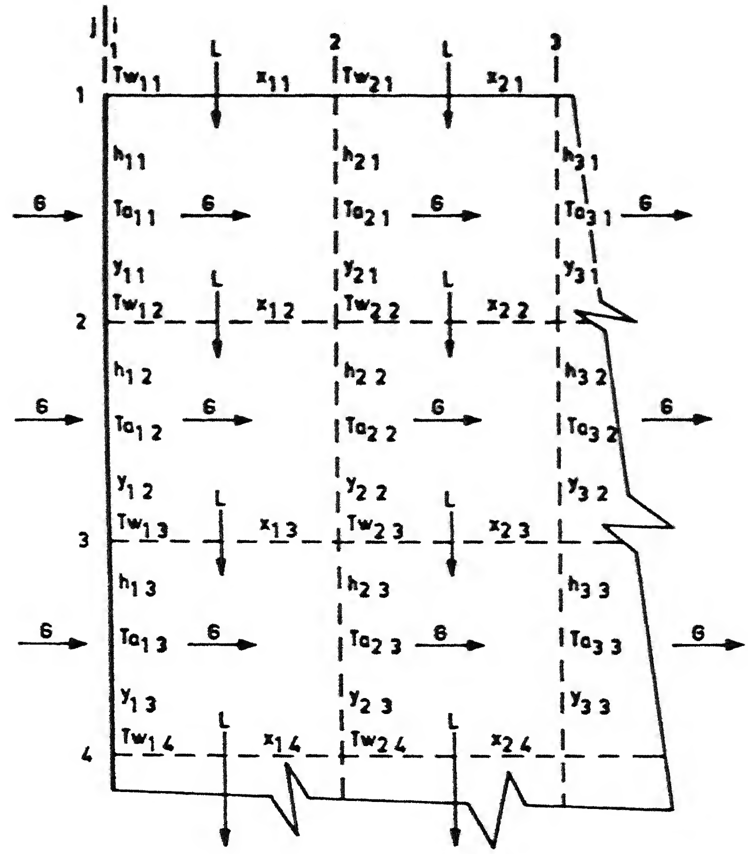

Fig. 6. Schematic representation of crossflow ammonia stripping tower.

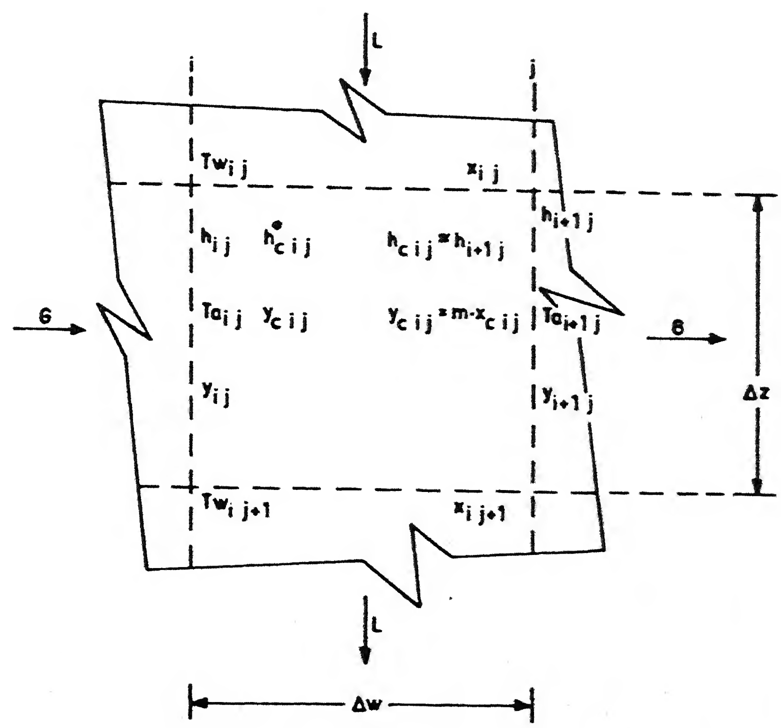

Fig. 7. Details of an element of crossflow ammonia stripping tower.

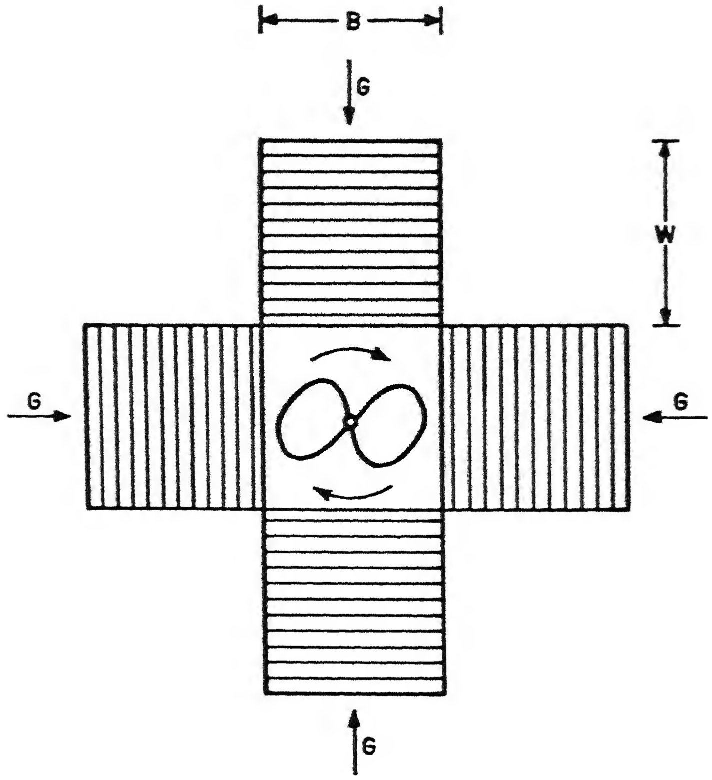

Fig. 8. Conceptual plan of crossflow ammonia stripping tower.

$$G' (h_{i+1\ j} - h_{i\ j}) \ \triangle z = L' (Tw_{i\ j+1} - Tw_{i\ j}) C_p \triangle w \quad \text{................(15)}$$

$$h_{i\ j} - h_{i+1\ j} = (1/HT) (h^*_{cij} - h_{cij}) \quad \text{................(16)}$$

where, h_{ij} and h_{cij} are the enthalpies of air at the entrance and at the centre of an element (i j) respectively, h^*_{cij} is the enthalpy of air at the centre of element (i j) corresponding to the water temperature, and Tw_{ij} is the temperature of water at the entrance of the element (i j). Eq. 15 is the difference form of Eq. 14. Substituting $\triangle z = \triangle w$ in Eq. 15, the following equation can be obtained

$$G' (h_{i+1\ j} - h_{i\ j}) = L' (Tw_{i\ j+1} - Tw_{i\ j}) C_p \quad \text{................(17)}$$

Empirical regression relationships given by Eqs. 8 and 9 are used to relate enthalpy and wet-bulb temperature of air. The algorithm for calculation of temperature profile is given in Fig. 9.

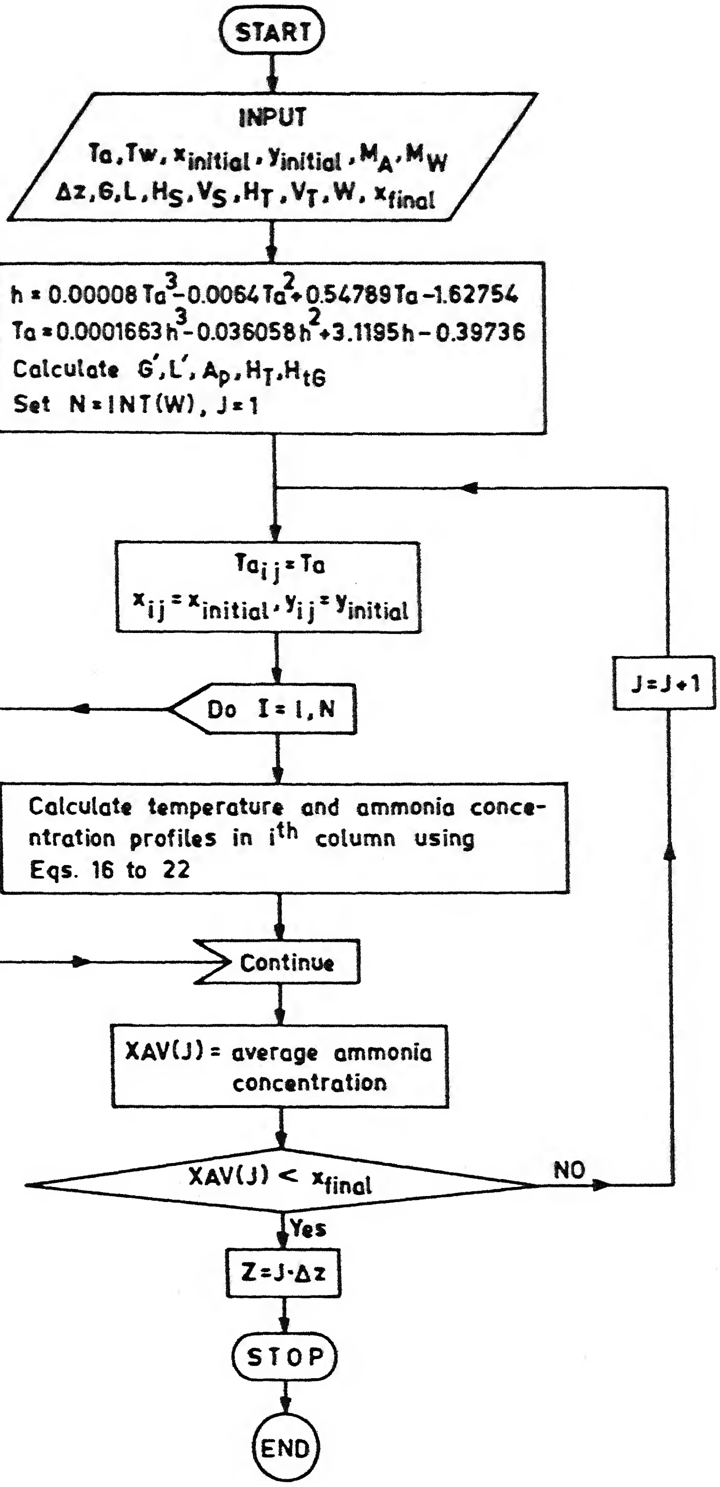

Fig. 9. Flow chart for computing temperature and ammonia concentration profiles in crossflow ammonia stripping tower.

Computation of Ammonia Concentration Profile

The equations used for computation of ammonia concentration profile are developed based on mass balance and mass transfer relations with reference to Figs. 7 and 8.

$$x_{i\ j+1} = \left[\frac{(2.A/BB) + A - m}{(2.A/BB) + A + m}\right] x_{i\ j} + \left[\frac{2}{(2.A/BB) + A + m}\right] y_{i\ j} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(18)$$

where,

$$m = 0.1117\ e^{0.02612(1.8Tw_{i\ j} + 32.0)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(19)$$

$$A = L/G \qquad \ldots\ldots\ldots\ldots\ldots\ldots(20)$$

$$BB = \Delta w/H_{tG} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(21)$$

and

$$y_{i\ j} - y_{i+1\ j} = L/G\ (x_{i\ j+1} - x_{i\ j}) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(22)$$

Here, x_{ij} and y_{ij} are the ammonia concentrations in liquid and gaseous phase at the entrance of element (i j) respectively. The algorithm for calculation of ammonia concentration profile is given in Fig. 9.

Computation of Air Pressure Drop

The air pressure drop in a crossflow tower is related to air flow rate, width of the tower, nature of packing and density of air. The relationships used in the present study are adopted from Kelly and Swenson (1956). According to these relationships, the pressure drop consists of two components:

1. the pressure drop caused by filling and support members.

$$\Delta P_1 = (4.77\ .\ \alpha\ .\ G'^2.\ W)/(H_S \rho) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(23)$$

where, α is a constant equal to 0.26×10^{-8}, W is the width of an unit of a crossflow tower, and ρ is the density of air.

2. pressure drop due to obstruction by water drops.

$$\Delta P_2 = 2.24 \times 10^{-3}\ (\beta.\ S_F^{0.5}.\ L'.\ G_E^2.\ Z)/(V_S.\ \rho) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(24)$$

where, β is a constant equal to 0.07×10^{-8}, G_E is the equivalent air mass velocity for pressure drop relation given by

$$G_E = \sqrt{[(0.0422\ G'^2) + (489.15\ G' . \rho . S_F^{0.5}) + (1596029.0\ \rho^2 . S_F)} \quad \text{.................(25)}$$

and S_F is the vertical fall of a water drop used in pressure drop calculations and is given by

$$S_F = 0.0328\ (V_S . H_S / H_T) \quad \text{.................(26)}$$

The total pressure drop is the sum of the two i.e. $\Delta P = \Delta P_1 + \Delta P_2$

OPTIMAL DESIGN

Optimization, as used here, is the determination of the design of an unit process such that it achieves desired effluent goals as for as possible and at the same time results in minimum capital and operation costs during the design life time of the system. The term "design" means the sizes of the system components and their operational requirements. There are three preliminary steps that must be completed prior to the optimization of a treatment process. First, the system must be defined in terms of unit process model. Second, specific input values of parameters of the model must be determined. Third, limitations on operating characteristics of equipment must be obtained. With these sets of information and appropriate cost data, optimization is simply a matter of formulating the optimization problem and finding a suitable solution technique.

Unit Process Model

The process model used to describe ammonia stripping tower (counter and cross current), has been described in earlier sections. To achieve the desired effluent ammonia concentration, preheating of water and/or air, particularly at low operating temperatures, may be required. Thus two options are considered:

1. Design of tower without preheating water and/or air, and
2. Design of tower with preheating water and/or air.

Process Data Requirements

Successful application of the optimization procedure described here requires that appropriate values of the process data are available. These include height of transfer unit for heat transfer HT, and height of transfer unit for mass transfer H_{tG}. Also the type of packing used should be suitably described (by assigning suitable values to H_T, V_T, H_S and V_S) and corresponding value of fanning friction factor f should be assumed. These values can be obtained from pilot plant studies or the literature (Roesler et al., 1971).

Formulation of the Optimization Problem

Once the process models and input data have been obtained, the next step in system optimization is the formulation of the problem itself. In general, optimization problems have the following format.

Minimise $F = f(x_1, x_2, x_3, \ldots\ldots, x_n)$ ....(27)

subject to the constraints

$g_j(x_1, x_2, x_3, \ldots\ldots\ldots\ldots, x_n) \leqslant 0; \; j=1,2,\ldots,m$ ....(28)

The independent variables of the objective function are called decision or design variables. They represent quantities that define the system. The set of specific values of these variables which minimise the objective function is defined to be the optimal design. The set of Eqs. 28 make up the constraint set. These equations set limits on the design variables. They are derived from limitations on equipment, space or other scarce resources, production requirements, or any other restrictions on variables that are functions of the design variables directly or indirectly. For ammonia stripping towers, the objective function is chosen as the sum of capital (converted to

annual) and annual operation costs. Capital cost can be converted to annual cost through capital recovery factor (CRF) for a given interest rate and system life time.

Annual Cost = Capital Cost . CRF ....(29)

where, CRF can be calculated as

$$CRF = [\, I\,(I + 1)^n \,]/[\,(1 + I)^n - 1\,] \quad \text{................(30)}$$

Here, I is the interest rate, and n is the design life of the system or its components. Thus the general form of the objective function is

TC = (Total Capital Cost) CRF + Total Annual Operation Cost ....(31)

where, TC is the total annual cost. The constraint equations are derived from considerations about practical and process aspects. The choice of design variables is the first step in formulating the objective function. A logical way to proceed is to first determine the variables that the cost equations are functions of, and than select design variables that fix values of these.

Counterflow Tower Without Preheating Water and/or Air

In this case the overall objective function can be written as

$$TC = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 \quad \text{................(32)}$$

where, C_1 is the cost of fan, C_2 is the cost of pumps, C_3 is the cost of the tower structure, C_4 is the exterior and electrical cost, C_5 is the cost of the distribution system, C_6 is the cost of packing material, C_7 is the fan power cost, C_8 is the pump power cost, and C_9 is the cost of chemical, labour and supplies.

An examination of the process model equations presented in earlier sections reveal that the designer has the choice of only two variables, namely G' and L'. Once these values are fixed, all other process design variabls are uniquely determined. Thus the opimization

of counterflow tower involves a design vector with two variables G' and L'. Constraints on these variables were obtained from literature (EPA, 1975) and practical considerations. Mathematically,

$1000 \leqslant L' \leqslant 20000$ ....(33)

$1.0 \leqslant G'/L' \leqslant 8.0$ ....(34)

$Z \geqslant 3.0$ ....(35)

The lower limit on liquid loading rate is put to ensure that all portions of the tower are equally wetted. The higher limit is put so that no flooding occurs in the tower.

Counterflow Tower with Preheating of Water and/or Air

In this case the overall objective function can be written as

$$TC = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 + C_{10} + C_{11} \qquad \text{................(36)}$$

where, C_{10} is the cost of heating air, and C_{11} is the cost of heating water. As mentioned earlier, the efficiency of ammonia stripping process reduces drastically at lower temperature. This warrants investigating the option of preheating water and/or air. Thus the cost of heating air and water must be incorporated into the cost of stripping tower. Therefore the optimization in this case involves a design vector with four variables G', L', the temperature of air after heating Ta_1, and temperature of water after heating Tw_1. The additional constriants on Ta_1 and Tw_1 can be expressed as

$Tw_1 \geqslant Ta_1$ ....(37)

$Tw_1 \geqslant Tw$ ....(38)

$Ta_1 \geqslant Ta$ ....(39)

$Tw_1 \leqslant 70.0$ ....(40)

Crossflow Tower Without Preheating Water and/or Air

In this case the overall objective function is same as that given by Eq. 32. The design vector consists of three variables G', L' and W. The configuration of the tower considered is shown in Fig. 6. The constraint in addition to those given by Eqs. 33 to 35 is as follows.

$$B/W \leqslant 4.0 \qquad \text{................(41)}$$

Crossflow Tower with Preheating of Water and/or Air

In this case the overall objective function is same as that given by Eq. 36. The design vector consists of five variables G', L', W, Ta_1 and Tw_1. The constraints are given by Eqs. 33 to 41.

Cost Data

Cost data is one of the most important input to any optimization problem. The cost functions for the ammonia stripping towers were taken from Roesler et al (1971). A summary of these cost functions is presented in Table 2. The cost for heating water and air for various temperature ranges are given in Tables 3 and 4 respectively. These values were obtained by considering that water and air were heated in heat exchanger with steam as the heating fluid. The cost of heating consists of cost of steam, capital cost of the heat exchanger and cost of pumping both process and utility fluids through the heat exchanger (Peters and Timmerhaus, 1979). In this regard it should be noted that the main expense incurred during preheating air and/or water is that of the utility fluid i.e. steam in this case. It is assumed that steam is available cheaply (as is the case in most industries), and the cost of steam was assumed accordingly. It is generally accepted that unless sufficient quantity of utility fluid is available cheaply, preheating of air and/or water is not feasible.

Table 2. Summary of cost data for counterflow and crossflow ammonia stripping towers.
(Adapted from Roesler et al., 1971)

Sl. No	Items	Cost function \$/year
1.	C_1 = Cost of fans.	$0.1175 \,.[14.06 \,.\, G' .\, A_c \,.\, \Delta P/ (\rho .E_f)]^{0.824} \,.CCI \,.CRF$
2.	C_2 = Cost of pumps.	$986.9 \,.[0.722 \,.Q \,.Z/E_p]^{0.44} + 37.95 \,.[0.722 \,.Q.Z]^{0.97} \,.CRF \,.CCI$
3.	C_3 = Cost of the structure.	$71.73 \,.\, [B \,.W] \,.Z^{1.462} \,.\, CRF \,.CCI$
4.	C_4 = Exterior and electrical cost.	$321.663 \,.[B \,.W] \,.CRF \,.CCI$
5.	C_5 = Cost of distribution system.	$2599.1 \,.\, Q \,.CRF \,.\, CCI$
6.	C_6 = Cost of packing.	$1.431 \,.[C_w \,.V_T \,.H_T/(V_S \,.H_S) \,.A^c \,.Z \,.CCI \,.\, CRF$
7.	C_7 = Fan power cost.	$0.241 \,.[\Delta P.\, G'.\, B.\, W.\, P_c.\, C_k./(\rho\, E_f) \,.CCI$
8.	C_8 = Pump power cost.	$0.023844 \,.[L' \,.B \,.W \,.(Z + 1) \,.P_c \,.C_k /E_p] \,.CCI$
9	C_9 = Cost of chemicals and labour.	$1.12\ [C_7 + C_8]$

Note: 1. For counterflow towers the expression [B.W] is repleced by cross sectional area of the tower A^c.

2. For crossflow towers expressions for C_3, C_4, C_6, C_7 and C_8 should be multiplied by a factor of 4.0.

Table 3. Cost in cents of heating 1000 Kg of water.

Initial Temp., °C	Final Temperature, °C 10	20	30	40	50	60	70
0	3.88	7.44	10.84	14.14	17.38	20.57	23.72
10	0.0	3.57	6.98	10.30	13.55	16.75	19.92
20	---	0.0	3.91	6.74	9.99	13.20	16.38
30	---	---	0.0	3.32	6.58	9.80	12.98
40	---	---	---	0.0	3.26	6.48	9.66
50	---	---	---	---	0.0	3.22	6.40
60	---	---	---	---	---	0.0	3.18

Table 4. Cost in cents of heating 1000 Kg of air.

Initial Temp., °C	Final Temperature, °C 10	20	30	40	50	60	70
0	1.85	3.36	4.69	5.91	7.05	8.14	9.19
10	0.0	1.51	2.84	4.06	5.20	6.29	7.34
20	---	0.0	1.33	2.55	3.69	4.78	5.82
30	---	---	0.0	1.22	2.36	3.49	4.49
40	---	---	---	0.0	1.14	2.23	3.28
50	---	---	---	---	0.0	1.09	2.13
60	---	---	---	---	---	0.0	1.05

The capital costs of structures, fans and pumps were transformed to an annual basis by using Eq. 31 taking design period to be 20 years and the rate of interest of 5 percent. This gives a value of CRF equal to 0.08024. Further the costs of the ammonia stripping tower and those of heating water and air were for different base year and thus they

were brought to the same year, 1987, by using suitable cost index factors (Engineering News Record, 1987).

Optimization Algorithm

Since the cost functions and constraints are nonlinear in design variables, interior penalty function method originally proposed by Caroll (1964) has been used. In this method the constrained nonlinear optimization problem is converted to unconstrained problem. A new function (φ - function) is constructed by augmenting a penalty term to the objective function. The penalty term is chosen such that its value will be small at points away from the constraint boundaries and will tend to infinity as the constraint boundaries are approached. Caroll (1964) proposed the penalty function as

$$\varphi(X, r) = F(X) - r \sum_{j=1}^{m} [1/g_j(X)] \qquad \text{................(42)}$$

where, r is the penalty parameter. The penalty term in Eq. 42 is not defined if X is infeasible i.e. any of the $g_j(X) > 0$. It has been shown (Fiacco and McCormic, 1968) that as r --> 0

$$\min \varphi(X , r) \longrightarrow F (X^*)$$

where, $F (X^*)$ is the minimum of F (X) and X^* is the design vector at the optimum point. The penalty function is sequentially minimized for decreasing sequence of r, until r approaches zero. This is known as Sequential Unconstrained Minimization Technique (SUMT) and uses any (e.g. Davidon-Fletcher-Powell method with cubic interpolation for one dimensional minimization as used here) of the unconstrained minimization methods (Rao, 1978).

RESULTS AND DISCUSSIONS

Application of optimization procedures developed in the present work is demonstrated through evaluation of optimal design for several

combinations of influent and process variables for both counter and cross flow packed bed towers with and without heating influent water and/or air. The typical results are presented in graphical/tabular form in this section.

Fig. 10 shows a typical plot of objective function and penalty function versus the number of SUMT cycles for counterflow tower. The

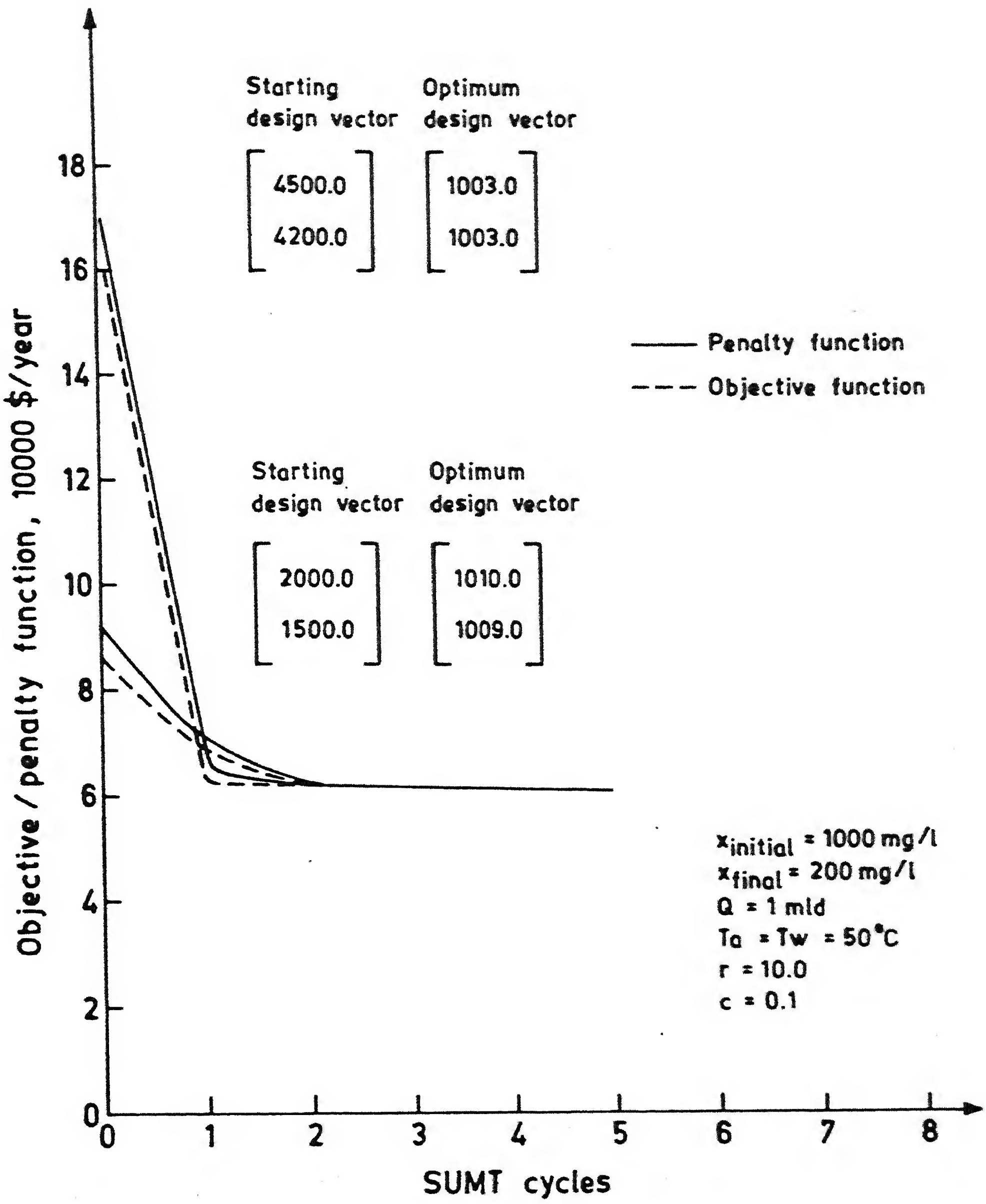

Fig. 10. Variation of objective and penalty function with SUMT cycles for a counterflow tower.

penalty function is always greater than the objective function by the positive penalty term. As the number of cycles increases or penalty parameter approaches zero, the penalty term decreases and hence the difference between penalty function and objective function narrows down. At the end as r --> 0, the penalty and objective function are essentially the same. It can be seen from Fig. 10 that two different starting designs lead to same optimal design indicating independence of the optimal result from the starting design vector. Similar results were obtained for crossflow towers.

The design vector for counterflow towers consists of only two variables and hence optimization results can be represented graphically in two dimensional space (Fig. 11). Feasible design space is mapped as a subset of the design space (set of all possible combinations of design variables, G' and L') enclosed by constraint boundaries (Eqs. 33 to 35). To get a better picture of the nature of the objective function surface very close to the optimal point, a three dimensional representation of a portion of the feasible design space is shown in Fig. 12.

A detailed study was conducted to investigate the effect of influent water and air temperatures and flow rate on the total unit cost of counter and cross flow towers. A summary of results is presented in Tables 5 and 6. Fig. 13 shows typical variation of cost and height of the counterflow tower as a function of influent air and water temperatures. The variation in cost components as a function of flow rate for crossflow towers is shown in Fig. 14. In general following inferences can be drawn from the results presented in Figs. 13 and 14, and Tables 5 and 6.

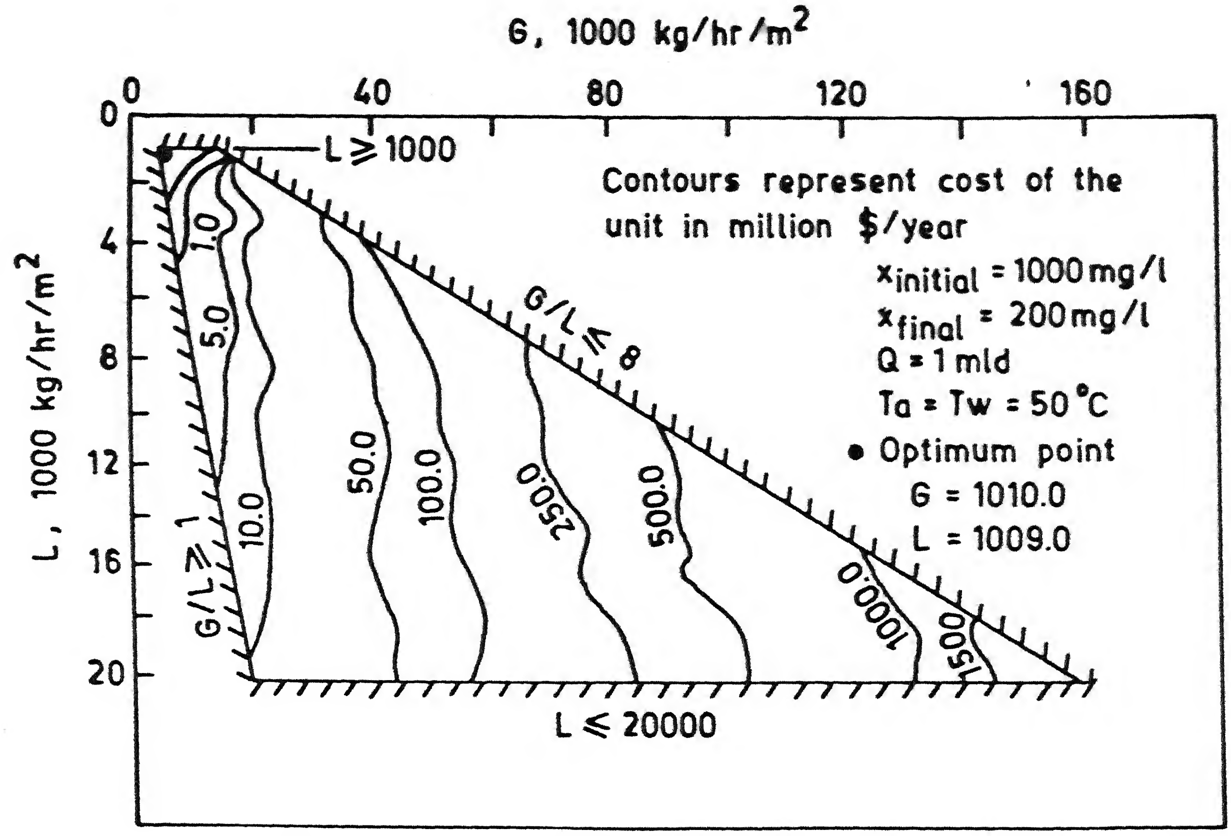

Fig. 11. Graphical represe' ation of constraints and objective function for counterflow towers.

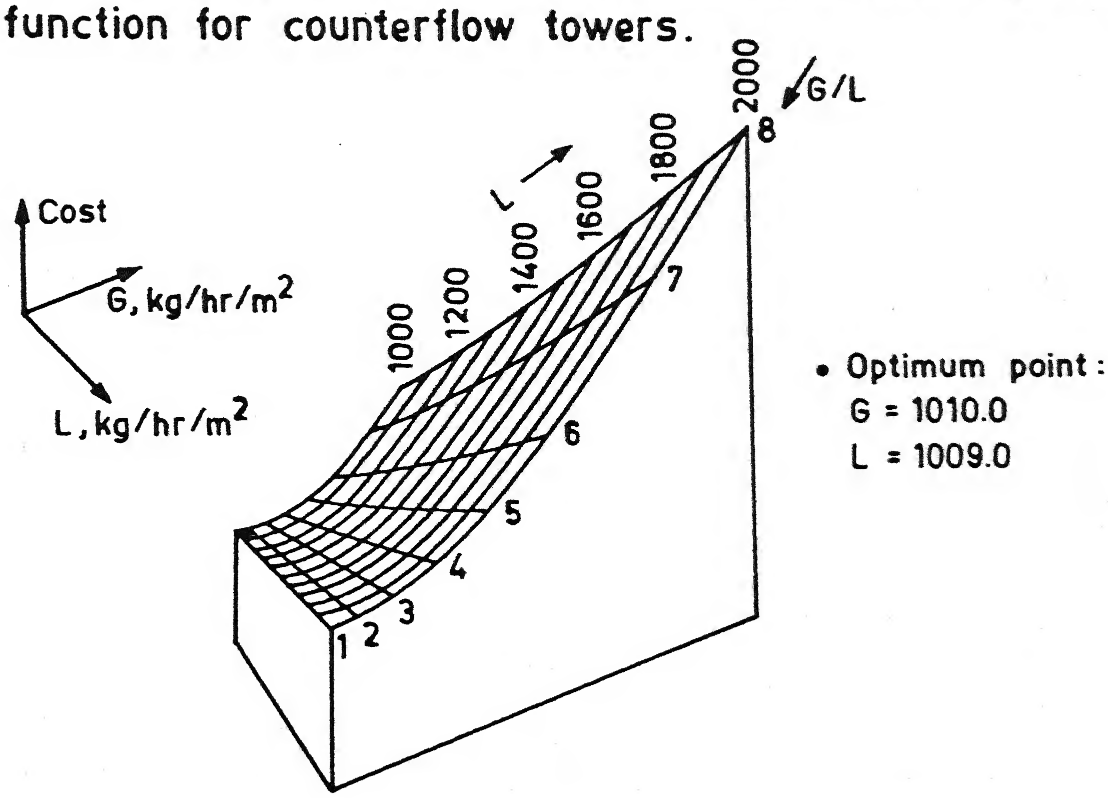

Fig. 12. Representation of the nature of the objective functio

Table 5. Summary of optimal designs of counterflow towers for different input conditions.

	Q	Z	X_{all}	G'	L'	G/L	A^c	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	TC
$T_a = T_w = 50°C$	1 mld	1.64	200.0	1010.0	1009.0	770.0	41.0	9.1	250.0	1093.0	2645.0	521.0	153.0	3480.0	23210.0	29894.0	61258.0
	2 mld	1.64	200.0	1107.0	1069.0	796.0	77.0	19.0	344.0	2064.0	4994.0	1043.0	290.0	8493.0	46420.0	61503.0	125171.0
	5 mld	1.64	200.0	1006.0	1003.0	770.0	206.0	34.0	530.0	5499.0	13305.0	2606.0	773.0	17322.0	116051.0	149379.0	305503.0
	10 mld	1.64	200.0	1013.0	1013.0	769.0	408.0	61.0	743.0	10888.0	26345.0	5212.0	1530.0	35021.0	232103.0	299179.0	611078.0
$T_a = T_w = 30°C$	1 mld	5.57	200.0	1859.0	1003.0	1425.0	41.0	102.0	441.0	6584.0	2662.0	521.0	525.0	65753.0	69631.0	151630.0	297854.0
	2 mld	5.90	200.0	1784.0	1031.0	1331.0	80.0	169.0	632.0	13921.0	5177.0	1042.0	1082.0	120599.0	146998.0	299710.0	589335.0
	5 mld	5.57	200.0	1815.0	1001.0	1394.0	211.0	372.0	971.0	33703.0	13626.0	2606.0	2691.0	314674.0	348155.0	742368.0	1459169.0
	10 mld	5.57	200.0	1807.0	1014.0	1370.0	408.0	634.0	1396.0	65123.0	26329.0	5213.0	5200.0	600042.0	696310.0	1451951.0	2852165.0

Note : 1. G/L is in M^3/M^3.

2. All other variables have the units mentioned in the nomenclature.

Table 6. Summary of optimal designs of crossflow towers for different input conditions.

	Q	Z	X_{all}	G'	L'	G/L	B	W	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	TC
$Ta = Tw = 50°C$	1 mld	1.64	149.0	1033.0	1032.0	769.0	7.06	1.76	26.1	1213.0	1069.0	2586.0	521.0	150.0	4120.0	23210.0	30610.0	63506.0
	2 mld	1.96	150.0	1058.0	1031.0	770.0	10.09	2.51	53.0	1790.0	2793.0	5176.0	1042.0	360.0	11444.0	54157.0	73474.0	150293.0
	5 mld	2.62	175.0	1070.0	1063.0	770.0	14.23	3.93	134.0	3070.0	10318.0	12557.0	2606.0	1167.0	45102.0	174077.0	245481.0	494517.0
	10 mld	3.28	183.0	1050.0	1014.0	771.0	21.13	5.57	273.0	4653.0	29965.0	26316.0	5213.0	3057.0	121115.0	425523.0	612235.0	1228355.
$Ta = Tw = 30°C$	1 mld	4.59	186.0	1035.0	1023.0	770.0	5.93	1.96	89.0	1917.0	4860.0	2610.0	521.0	424.0	7847.0	58025.0	73777.0	150075.0
	2 mld	5.24	196.0	1017.0	1004.0	769.0	9.07	2.62	159.0	2777.0	12034.0	5316.0	1042.0	988.0	18534.0	131525.0	168066.0	340444.0
	5 mld	6.88	185.0	1100.0	1049.0	790.0	14.47	3.93	445.0	4759.0	42850.0	12720.0	2606.0	3103.0	73544.0	425523.0	558955.0	1124509.
	10 mld	8.20	198.0	1094.0	1054.0	780.0	21.61	5.40	858.0	7107.0	110105.0	25330.0	5213.0	7358.0	182455.0	1005781.	1330825.	2675036.

Note : 1. G/L is in M^3/M^3

2. All other variables have the units mentioned in the nomenclature.

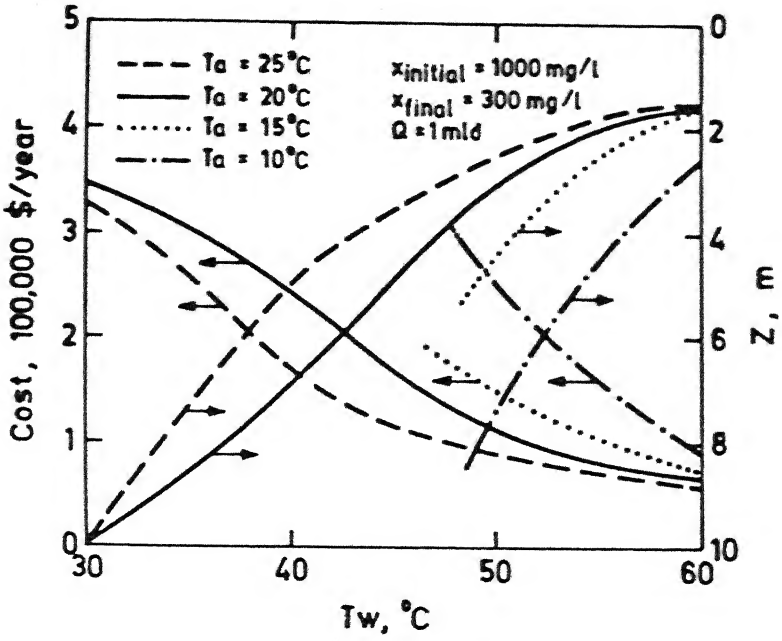

Fig. 13. Optimal cost of counterflow towers at various influent air and water temperatures.

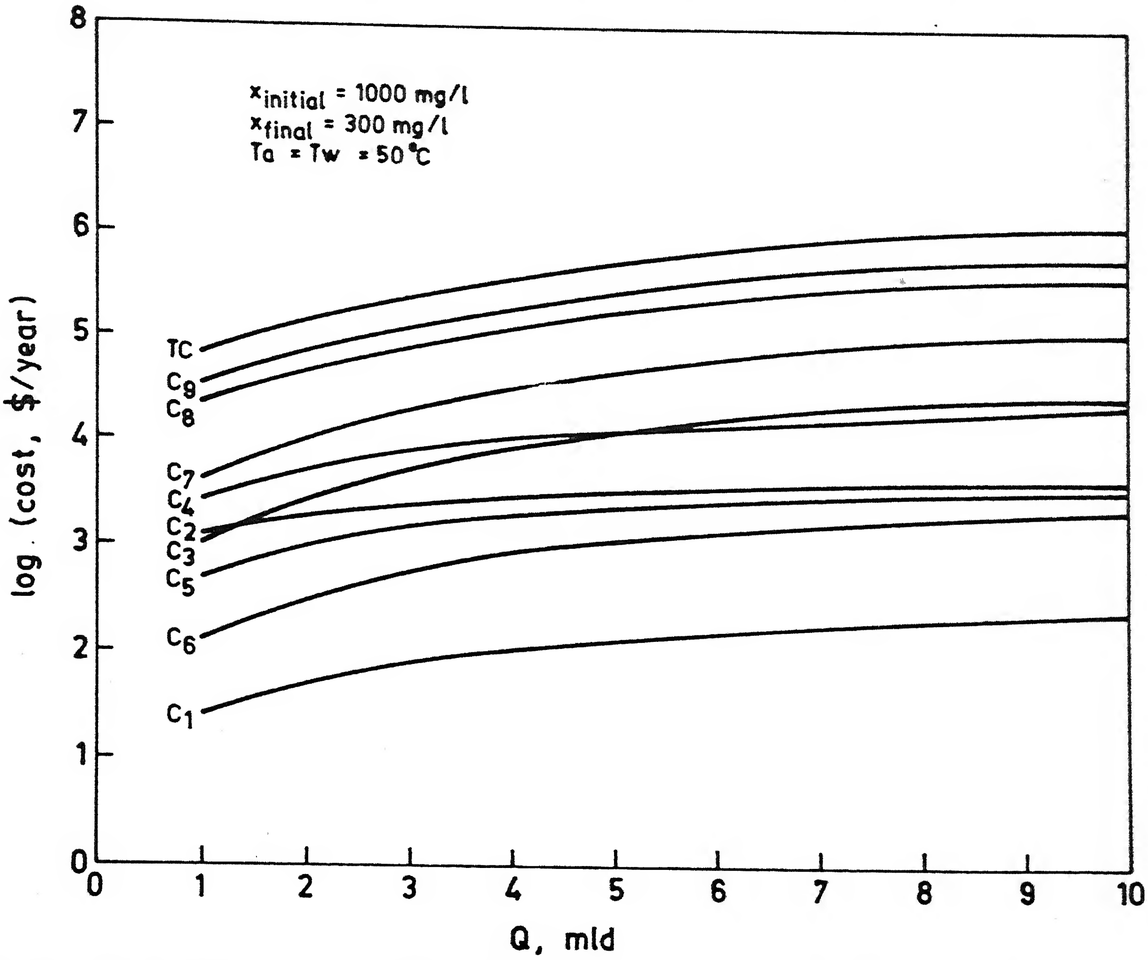

Fig. 14. The variation of various cost components with flowrate in crossflow tower.

- The optimal unit cost of the crossflow tower is lower than that of counterflow towers in most cases under similar input, output and system parameters.

- The optimal cost of the packed bed towers (cross and counter current) increases with decrease in influent water and air temperatures. The rate of increase of cost also increases with decrease in temperatures.

- The major portion of the cost consists of (i) the cost of electrical power for pumping liquid and blowing air, and (ii) chemicals and labour.

Investigations were also conducted for studying the effect of influent ammonia concentrations on the cost. It was noted that the change in initial ammonia concentration did not alter the cost of the unit significantly. Studies were conducted to ascertain the feasibility of preheating water and/or air to improve ammonia removal efficiency. The objectives of these studies were to find answers to the following questions.

1. Is it possible to achieve any reduction in cost of ammonia removal by preheating air and/or water in comparison to towers without heating arrangements ?

2. Is it possible to get the effluent ammonia concentration to below prescribed standards so that the effluent could be discharged into the receiving bodies without further treatment ?

Optimal designs were evaluated at different flow rates for several sets of parameters such as influent ammonia concentration in water, air and water temperatures and a target effluent ammonia concentration in water. Fig. 15 shows comparative cost of the units at different flow rates, and Figs. 16 and 17 present the various cost components i.e. cost of heating water, air, cost of the tower and total cost for counter and cross flow towers respectively. It is seen that substantial reduction in cost can be achieved by preheating water

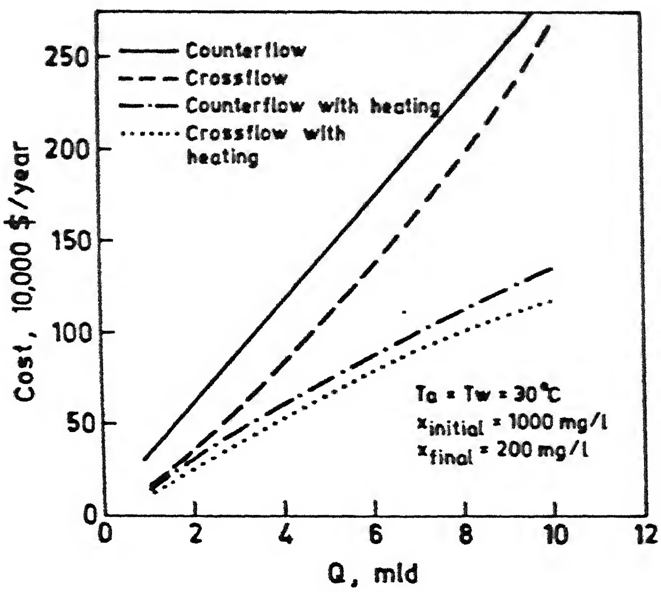

Fig. 15. Variation of optimal cost with flow rate.

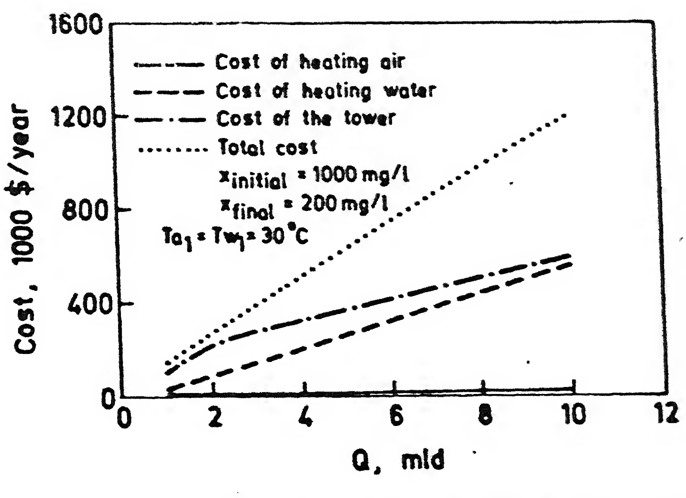

Fig. 16 Main cost components of the optimum design of counterflow tower (with heating).

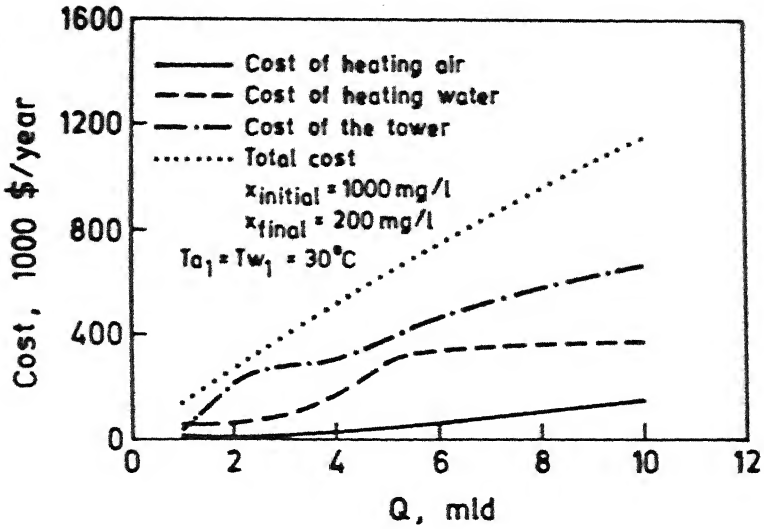

Fig. 17. Main cost components of the optimum design of crossflow tower (with heating).

and/or air. However, it should be noted that this observation is not universal and depends on the cost of heating water and/or air relative to that of the tower.

SUMMARY

In the present study optimization procedures were developed for minimum cost design of counter and cross flow ammonia stripping tower with and without the option of preheating water and/or air. The procedures are based on mathematical models of packed bed counter and cross flow ammonia stripping towers.

Computer programs were developed for the design and cost estimate of both counter and cross flow towers. These programs were then suitably modified to include them in the optimizaion program as subprograms. Optimization problem was framed as minimization of annual capital and operating cost subject to the constraints of process requirements. Optimization results of counterflow towers are presented in two dimensional space indicating constraint boundaries and cost

contours in feasible design space.

Comparison between counter and cross flow towers show that the latter are economical in most of the cases studied. The cost of the units vary almost linearly with flow rate. It was also noted that the cost of the system increases with decrease in influent air and water temperatures to achieve a certain degree of efficiency. However, influent ammonia concentration does not have any significant effect on the cost of the towers. The question of feasibility of heating water and/or air was studied in some detail. It was observed that for a given set of input, output and system parameters preheating of water and/or air leads to a lower cost.

Optimization procedures described in this thesis are general, but while going through the exercise of problem statement, formulation, execution and preparation of manuscript, few points were raised which could not be included in the scope of the present work. Following are a few suggestions to incorporate some of these points.

1. The height of transfer unit in a packed bed tower depends on the type of packing provided. In the present investigation wooden slats of a particular size were used as packing. It is desired that the user should have the option of using wooden slats of other sizes as well as other packing materials (e.g. raschig rings). Thus optimal design should be worked out for other packing materials.

2. An attempt should be made to develop an equation to evaluate optimal cost from a given set of input, output and system parameters. This can be achieved by fitting a regression curve after sufficient data have been generated.

3. The optimal design formulation should also include ammonia recovery system using absorption towers.

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